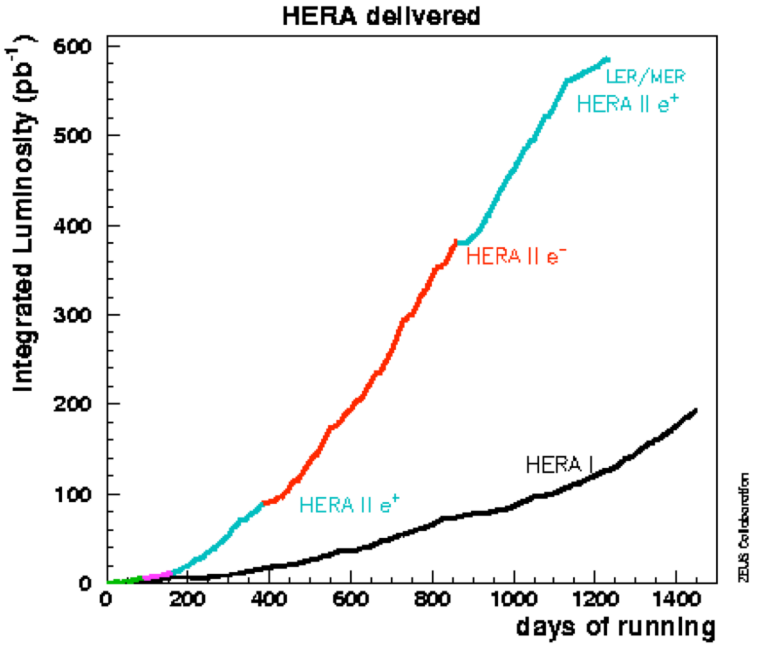
Experience of EW and BSM physics at HERA and lessons for EIC

Elisabetta Gallo (DESY and UHH)

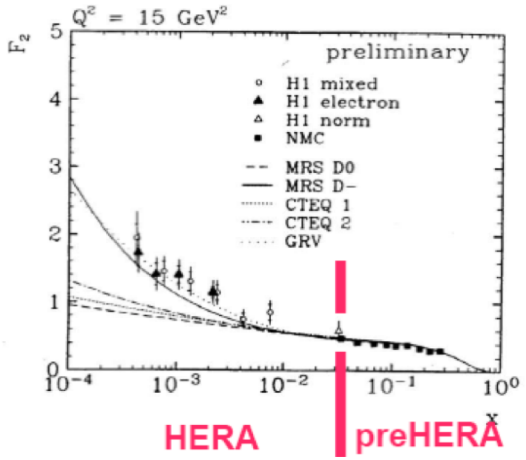
(A personal recollection and selection of topics)

Electroweak and BSM physics at the EIC, 6/5/2020

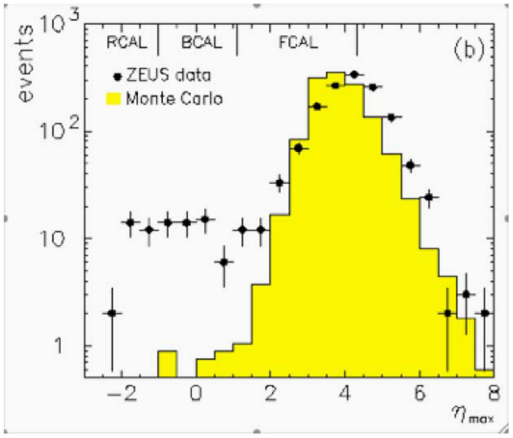
HERA (1992-2007)



First F_2 presented by H1 at Durham 1993

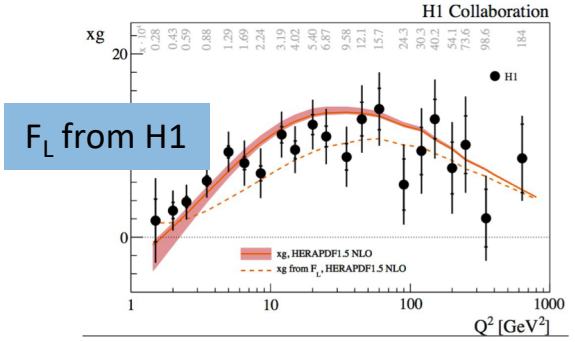


Diffractive events discovered by ZEUS, DESY seminar 1993



- HERA experiments were built for high Q^2 physics, but adapted very well to lower Q^2 low x
- With HERA II a stronger electroweak program could be started and searches boosted
- At the end of HERA II we went back to low-x physics with F_L

F_L from H1



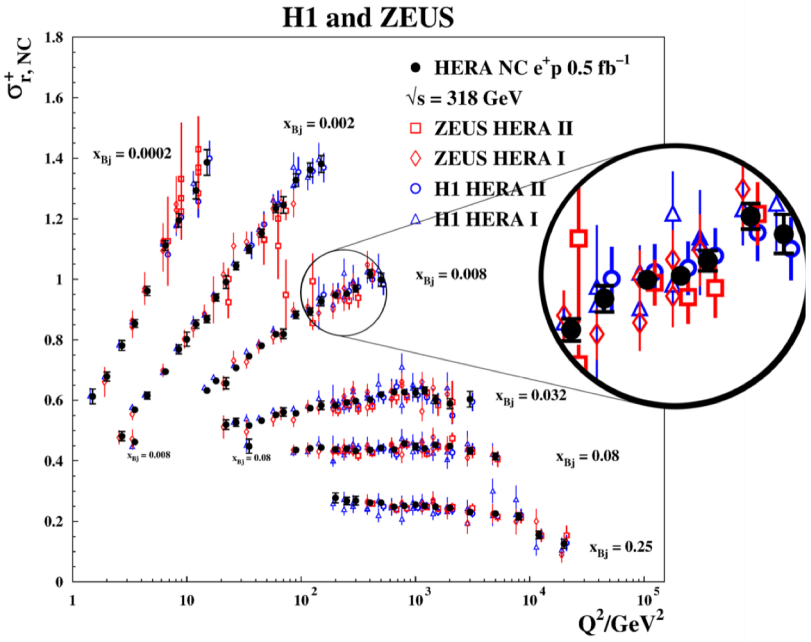
Increasing the luminosity (i.e. HERA II)

- Access to higher Q^2
  - Access to valence quark distribution at higher x in NC, xF_3
  - Electron vs positron running (endless discussions)
  - More precise measurements of charged current
  - Polarized beams
  - Combination H1-ZEUS data (it started for xF_3)
  - LHC was getting closer -> PDFs for LHC, more exchange, HERAPDFs
- More exotic searches
  - Isolated leptons plus missing energy and large hadronic p_T
  - Multilepton events
  - Leptoquarks
  - FCNC
  - Contact interactions

Triggered by observation in H1, no specific- related search

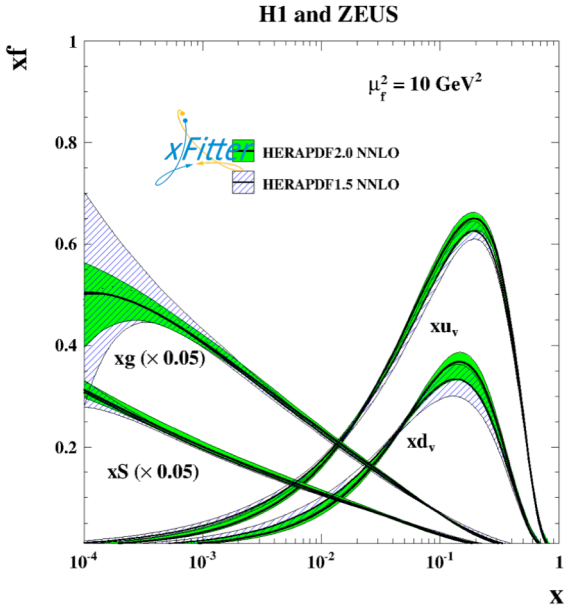
NC/CC at high Q^2

Few words about ZEUS and H1 combinations



EPJ C75 (2015) 580

ZEUS and H1 combination is the main dataset for PDFs fitters

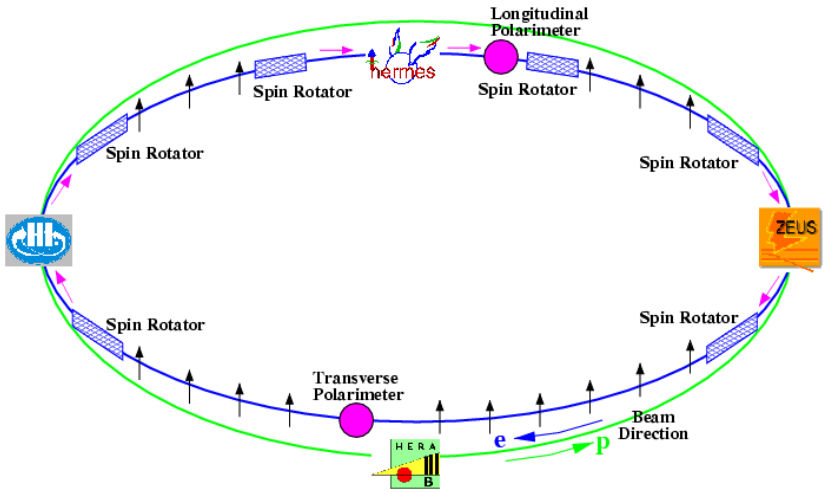


- xFitter, open-source tool originally started to fit PDFs at HERA
- Now used also for LHC experiments (EIC?)

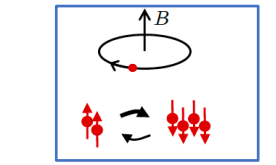
- Unless specified the plots I am going to show are based on the latest combined data
- And compared to HERAPDF2.0: based on data taken 1994-2007, 2927 points combined to 1307, 21 HERA I data samples, 20 HERA II data samples NC+CC

- NC: $0.045 < Q^2 < 50000$ GeV^2
  $6 \times 10^{-7} < x < 0.65$
- CC: $200 < Q^2 < 50000$ GeV^2
  $1.3 \times 10^{-2} < x < 0.40$

Polarization at HERA II

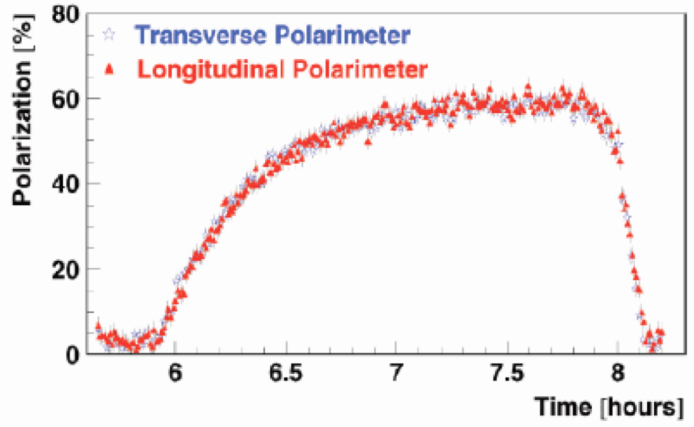


- Electrons/positrons get naturally transverse polarized (Solokov-Ternov effect)
- Spin rotators to change in long. polarization in the straight section before the experiments
- Polarization time ~ ½ h
- Polarization defined as:

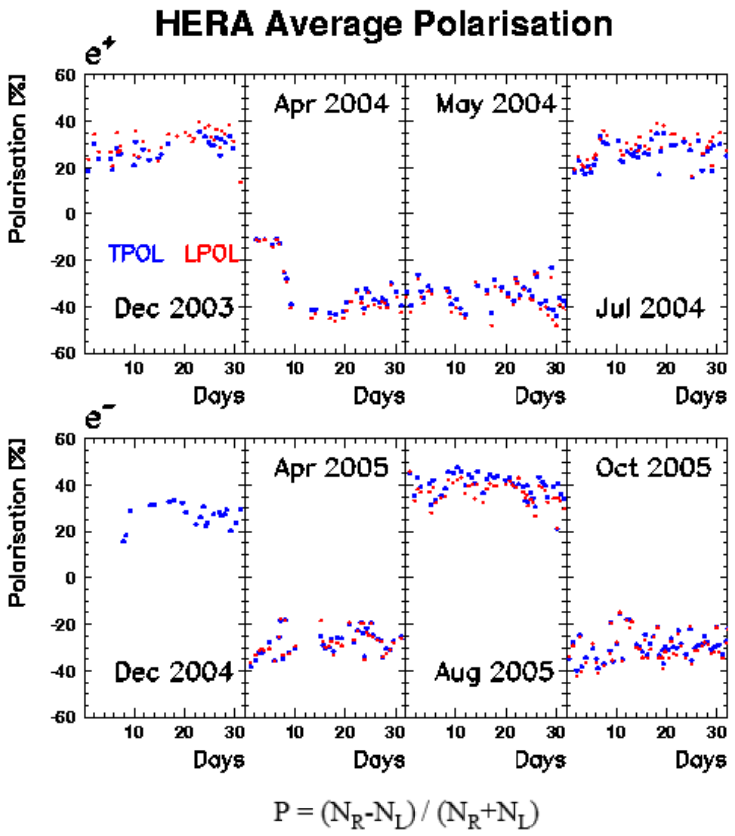


$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

- Polarization 30-40%
- Spin flip every 2-3 months
- Measured by three devices Tpol,Lpol and cavity
- Original aim was a precision of 1%, i.e. not contributing significantly to syst. errors

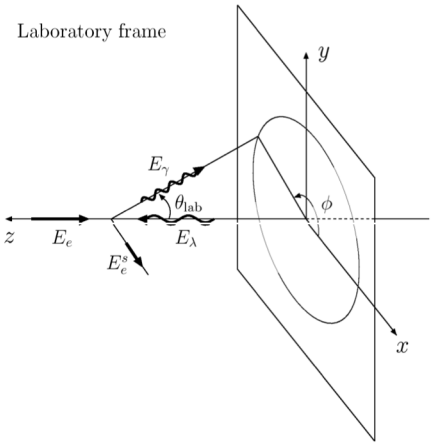


Polarization at HERA II



$P = (N_R - N_L) / (N_R + N_L)$

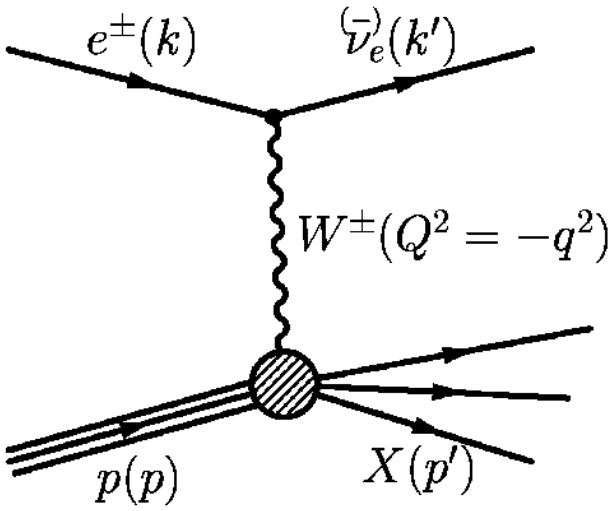
- Compton scattering cross section depends on polarization
- Circularly polarized laser beam off the electron/positron beam
- Asymmetry measured from scattered gamma in special calorimeters



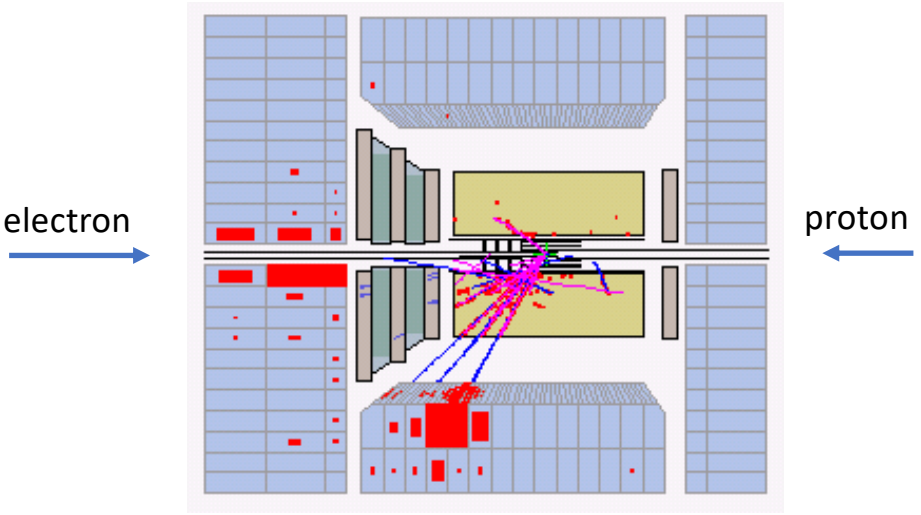
$$\frac{d^2\sigma}{dE\,d\phi} = \Sigma_0(E) + S_1\Sigma_1(E)\cos 2\phi + S_3 P_Y \Sigma_{2Y}(E)\sin\phi + S_3 P_Z \Sigma_{2Z}(E)$$

- TPOL: measured transverse polarization in straight West section, Sci-Tungsten e.m. calorimeter, +/- 1.9 % precision
- LPOL: measured longitudinal polarization in-between the HERMES spin rotators, compact Cherenkov crystal calorimeter, +/- 3.6% precision
- Note luminosity uncertainty: 1.8% ZEUS, 2.0% H1

Charged Current events at HERA



- Kinematics of reconstructed from hadronic system
- Hadronic calorimeter resolution crucial



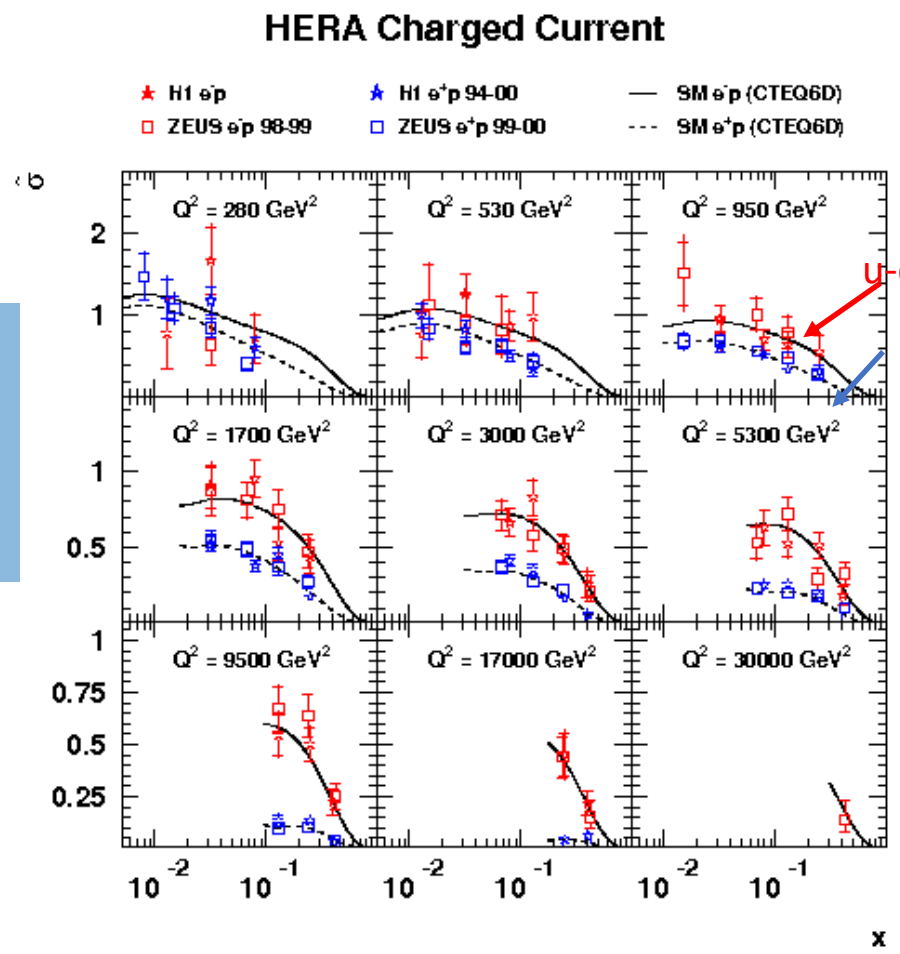
$$\frac{d\sigma^{e^+p}_{unpolCC}}{dQ^2dx} = \frac{G_F}{2\pi}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[\bar{u}_i(Q^2,x)+(1-y)^2 d_i(Q^2,x)\right]$$

$$\frac{d\sigma^{e^-p}_{unpolCC}}{dQ^2dx} = \frac{G_F}{2\pi}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[u_i(Q^2,x)+(1-y)^2\bar{d}_i(Q^2,x)\right]$$

- Both electron and positron running crucial
- e^+ p suppressed by (1-y)
- Give information on u,d valence density separately

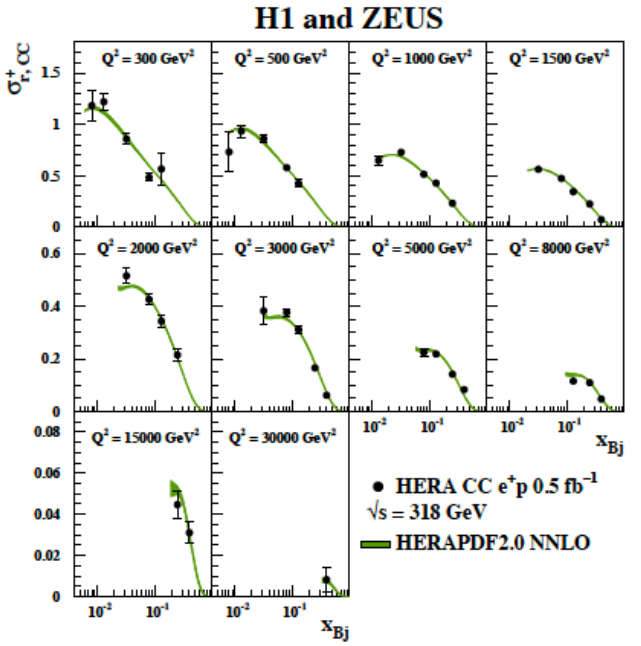
CC cross section

Earlier result



u-dominated

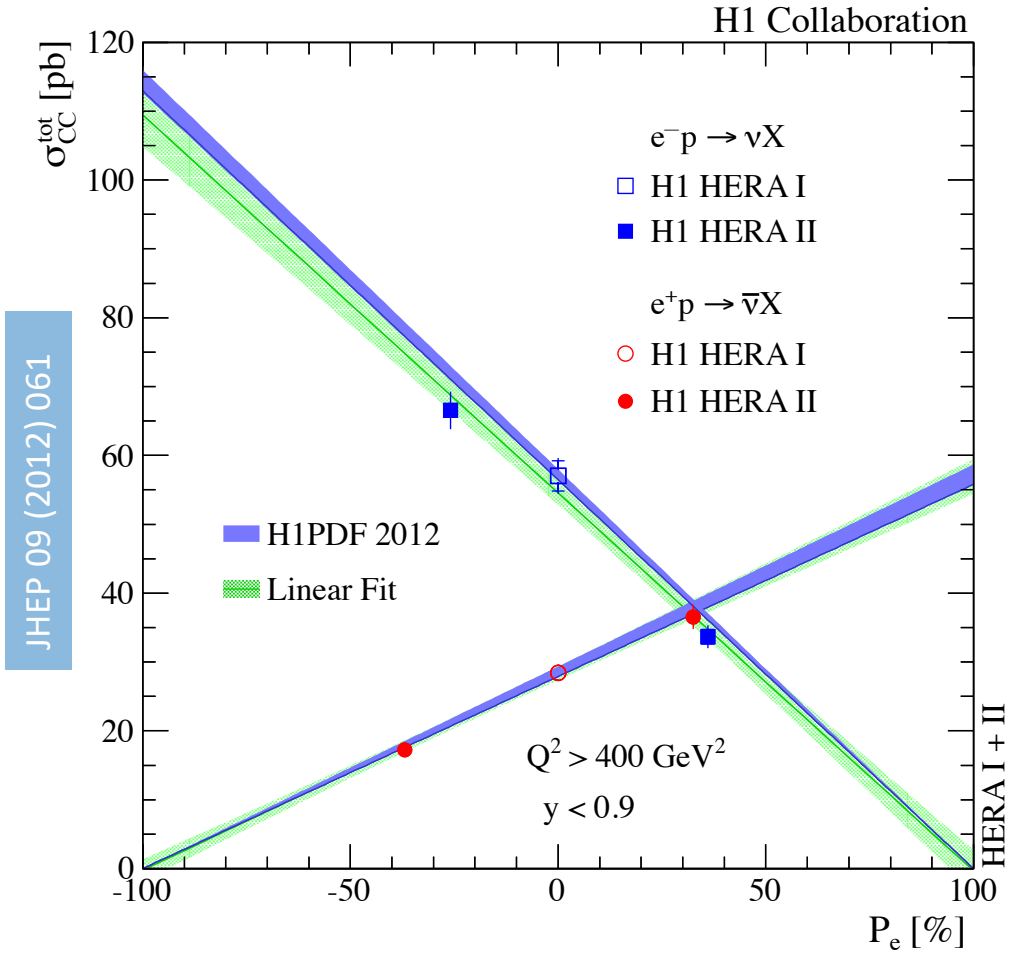
d-dominated



Combined data

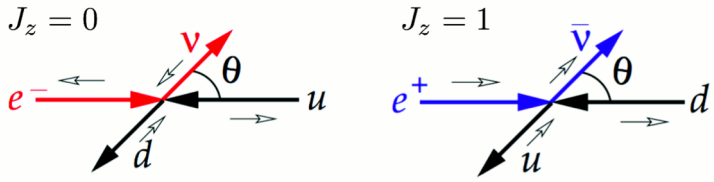
- Data important input to PDFs, i.e. u-valence and d-valence separation
- Complemented by W-charge asymmetry at the LHC these days, which is however at lower x

CC polarized cross section

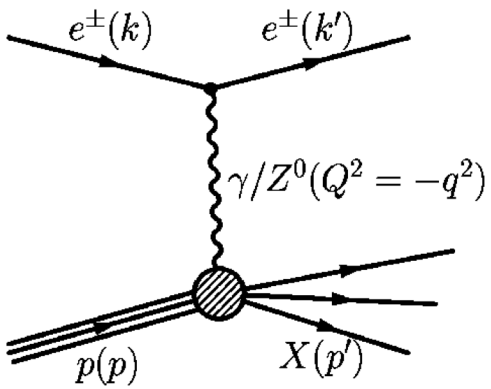


$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}(P_e)}{\mathrm{d}x\mathrm{d}Q^2} = (1 \pm P_e)\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

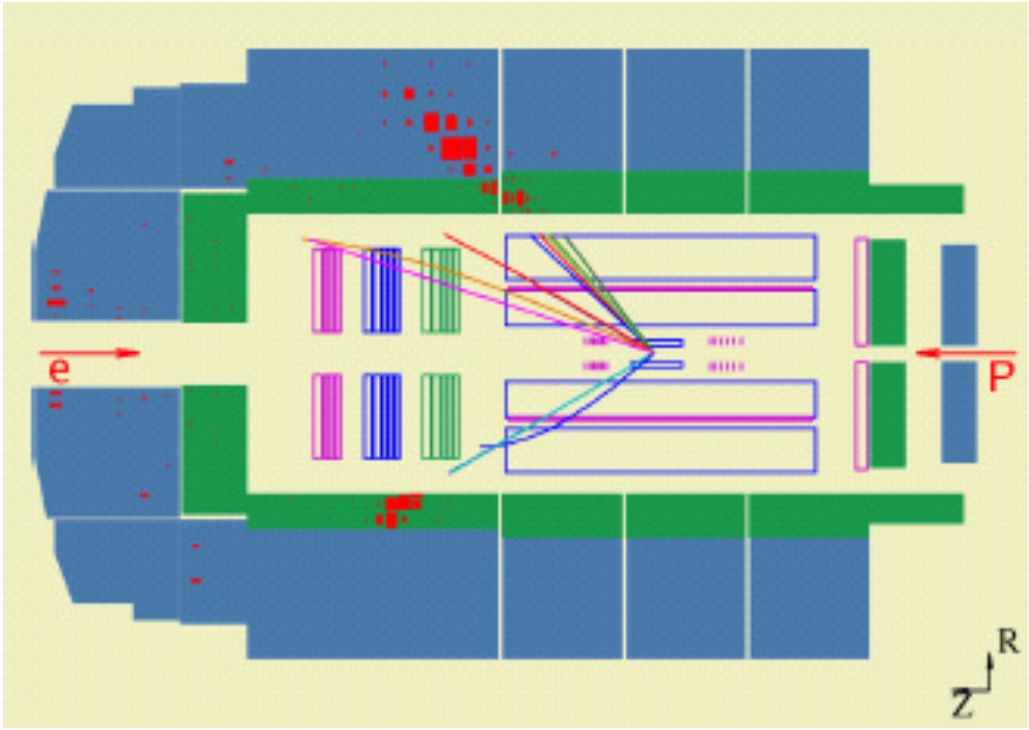
- Textbook plot: the charged current cross section goes to zero for right-handed electrons, as predicted by the SM



Neutral Current at high Q^2

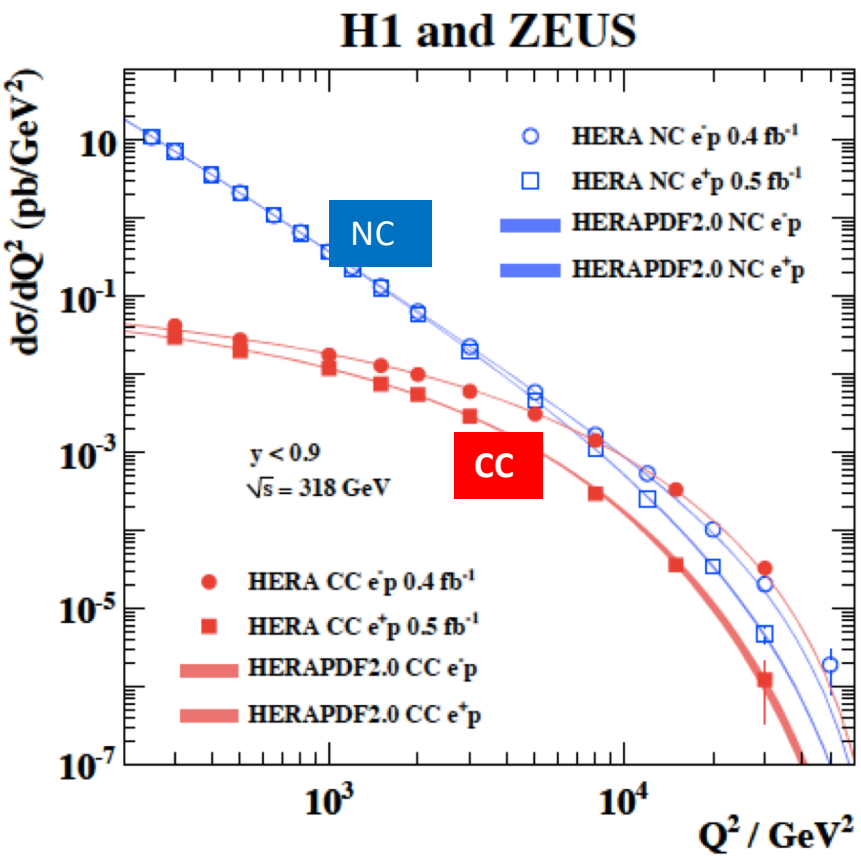


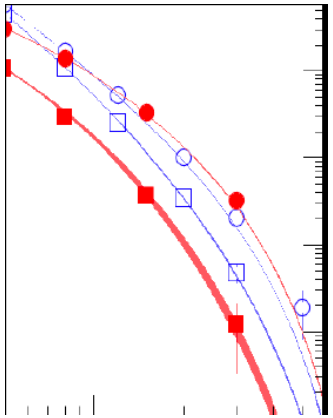
- Need electron identification at high angle, in the forward region, so optimized algorithm
- At high Q^2 the cross section (here expressed as reduced cross section) cannot neglect the xF_3 term



$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma^{\pm}}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^{\pm} \mp \frac{Y_-}{Y_+} x\tilde{F}_3^{\pm} - \frac{y^2}{Y_+}\tilde{F}_L^{\pm}$$

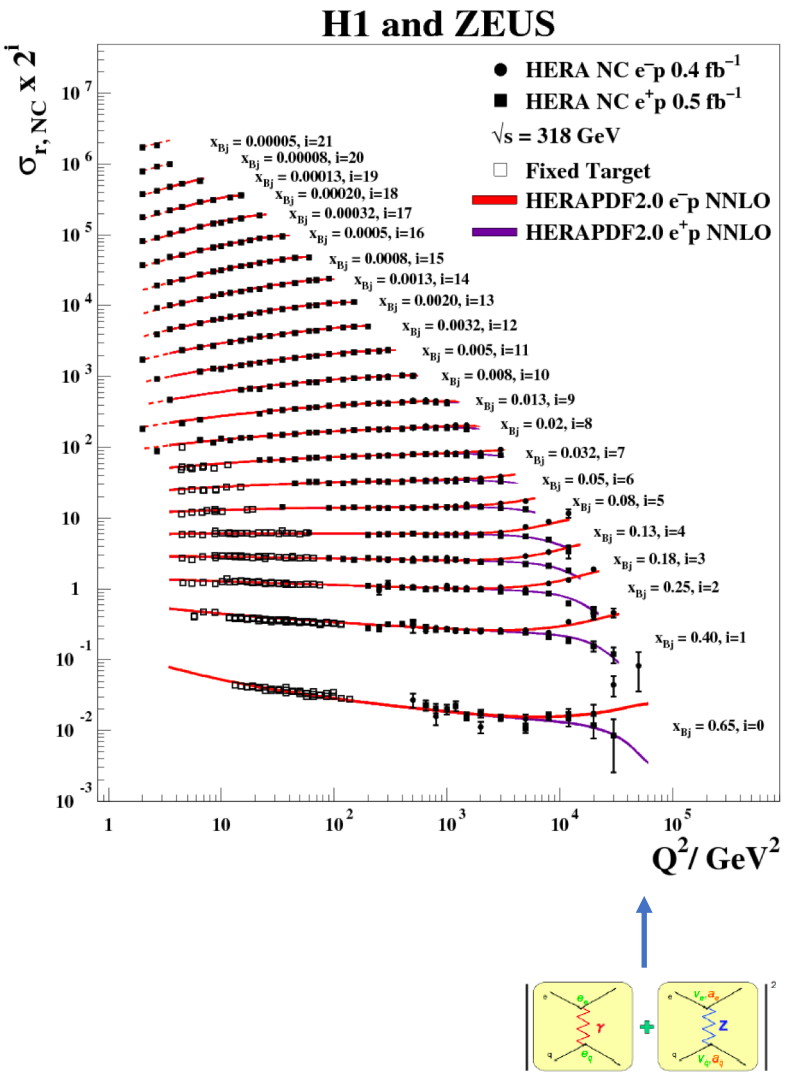
NC+CC cross sections





- Textbook plot: at high $Q^2 \sim M_Z^2$, M_W^2. become of the same strength
- Here shown with the QCD prediction with the HERAPDF2.0 fit
- In NC gamma-Z interference and Z-exchange visible at very high Q^2

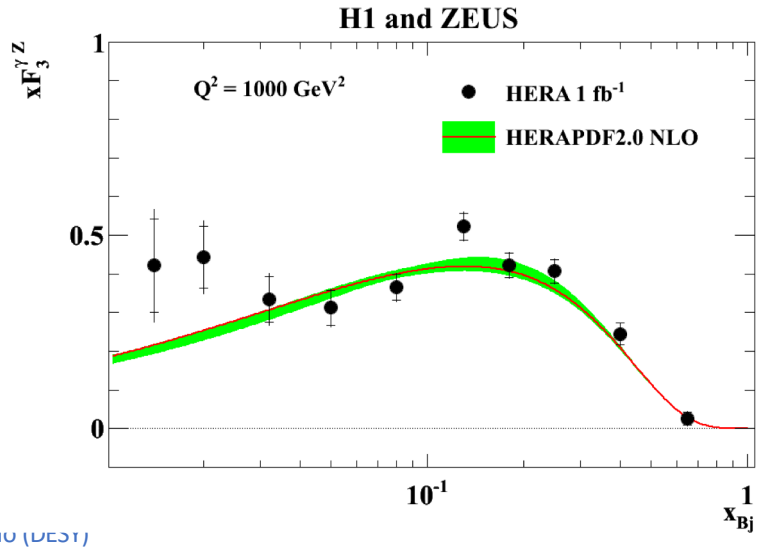
NC cross section



- Effect of Z-gamma interference clearly visible at high Q^2
- Measuring e^+ and e^- one can extract xF_3, directly sensitive to the valence quark distribution

$$xF_3^{\gamma Z} = x/3(2u_v + d_v + \Delta)$$

- Integral= $1.790 \pm 0.078\,(\text{stat})^{+0.078}_{-0.100}$ ~ 5/3 as predicted

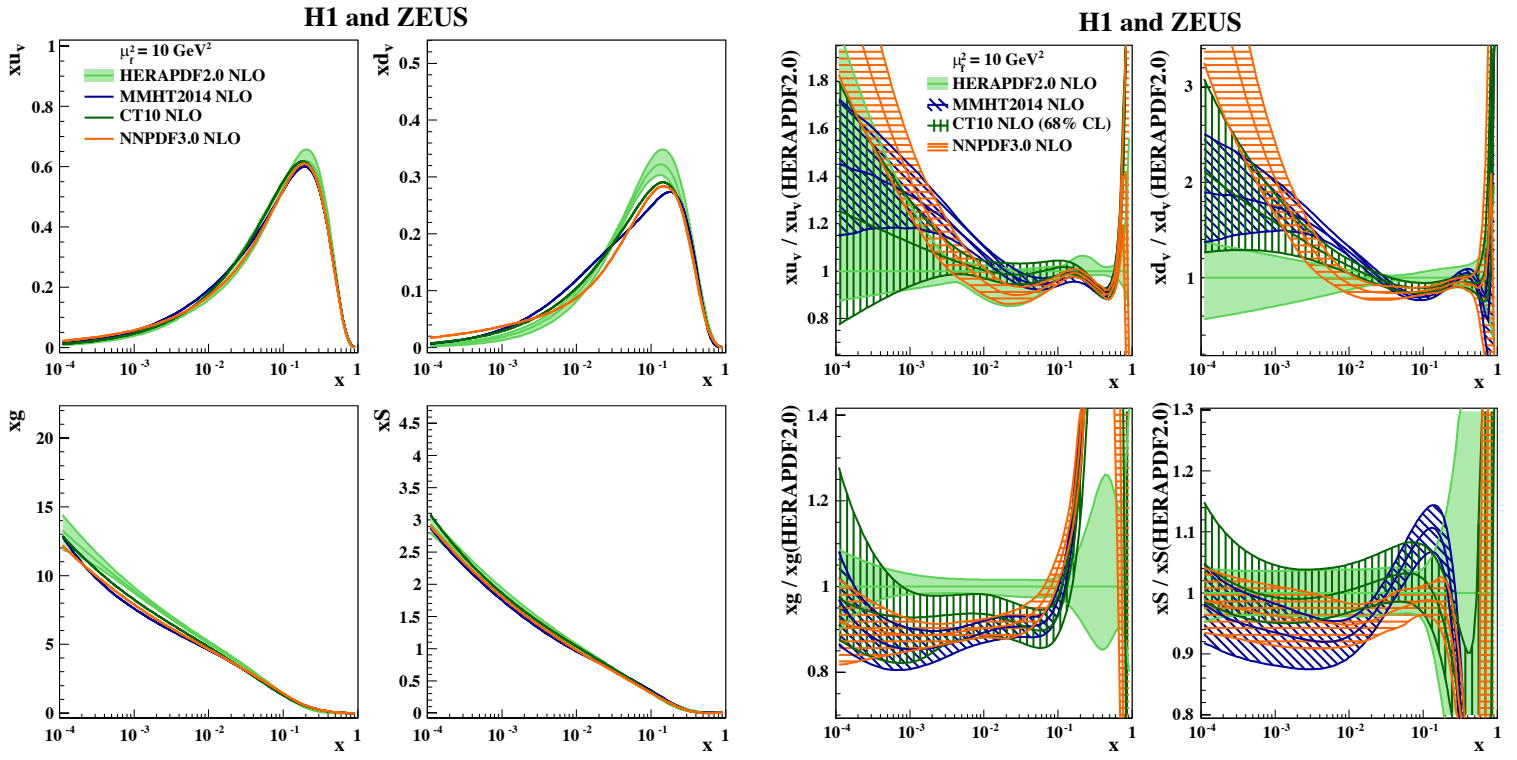


QCD fits – HERAPDF2.0

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

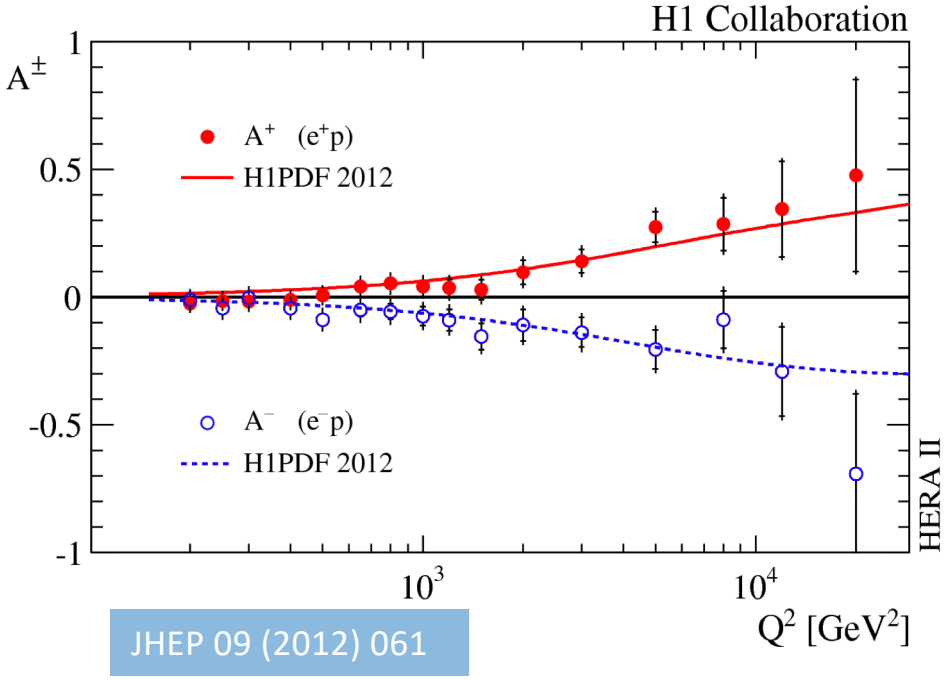
- 14 parameters fit
- Starting scale Q^2=1.9 GeV^2
- HQs from RT VFNS
- 5 orders of magnitude in x,Q^2 fit
- Chi^2/NDF=1357 /1131

PDFs extracted from these data



Polarized neutral current cross sections

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$



JHEP 09 (2012) 061

- Effect of polarization visible at very high Q^2
- Direct observation of parity-violation in NC

$$F_2^{L,R} = \sum_q [xq(x,Q^2) + x\bar{q}(x,Q^2)] \cdot A_q^{L,R},$$
$$xF_3^{L,R} = \sum_q [xq(x,Q^2) - x\bar{q}(x,Q^2)] \cdot B_q^{L,R}.$$

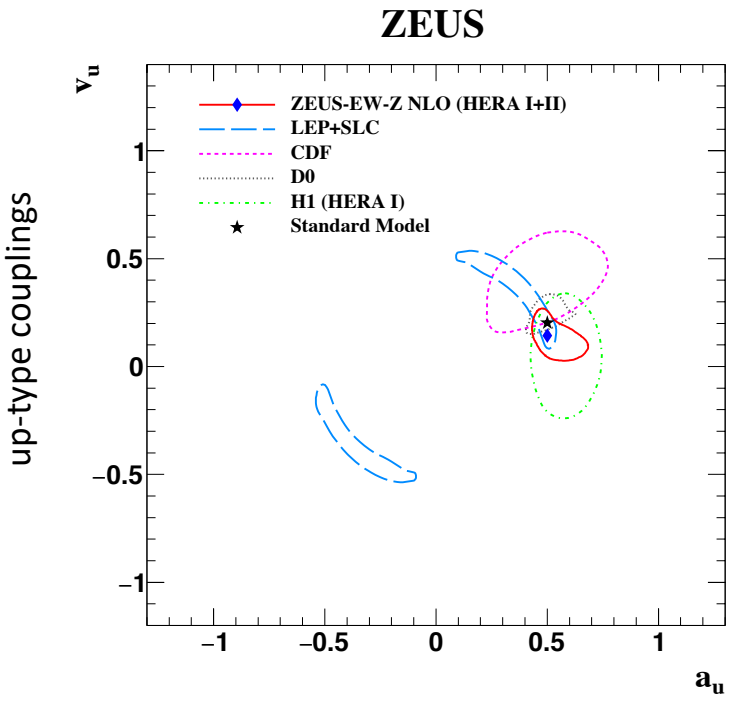
$$A_q^{L,R} = Q_q^2 + 2Q_eQ_q(v_e \pm a_e)v_q\chi_Z + (v_e \pm a_e)^2(v_q^2 + a_q^2)(\chi_Z)^2,$$
$$B_q^{L,R} = \pm 2Q_eQ_q(v_e \pm a_e)a_q\chi_Z \pm 2(v_e \pm a_e)^2 v_q a_q (\chi_Z)^2,$$

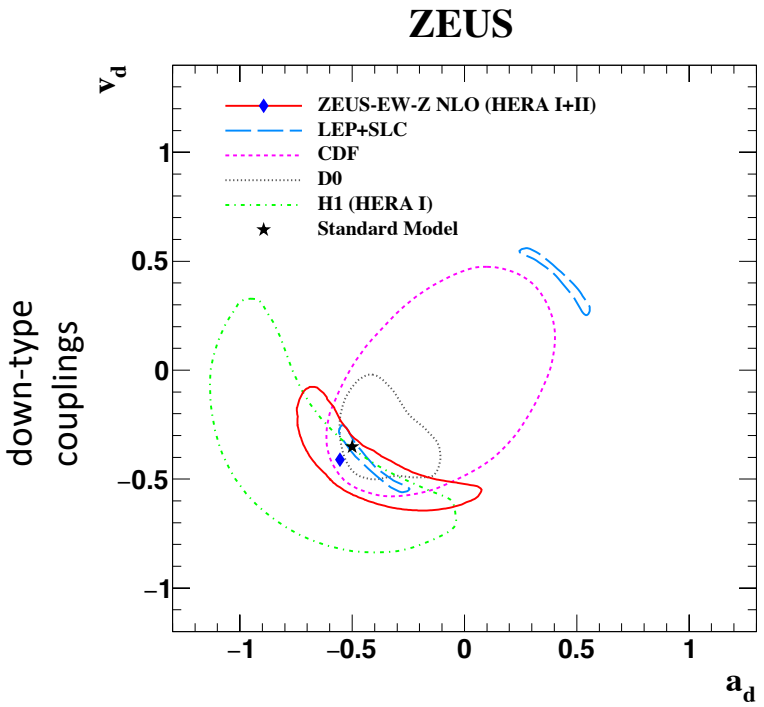
- Exploiting the polarization the u,d electroweak couplings to the Z can be determined, in quite a competitive way
  - Polarized F_2 constrains the vector couplings
  - Unpolarized xF_3 constrains the axial couplings
- Special QCD fits with EW parameters free

Combined QCD+EW fit ZEUS-EW-Z

$$v_u = 1/2 - 4/3 \sin^2\theta_W,\ a_u = 1/2$$

$$v_d = -1/2 + 2/3 \sin^2\theta_W,\ a_d = -1/2$$





Phys. Rev. D 93 (2016) 092202

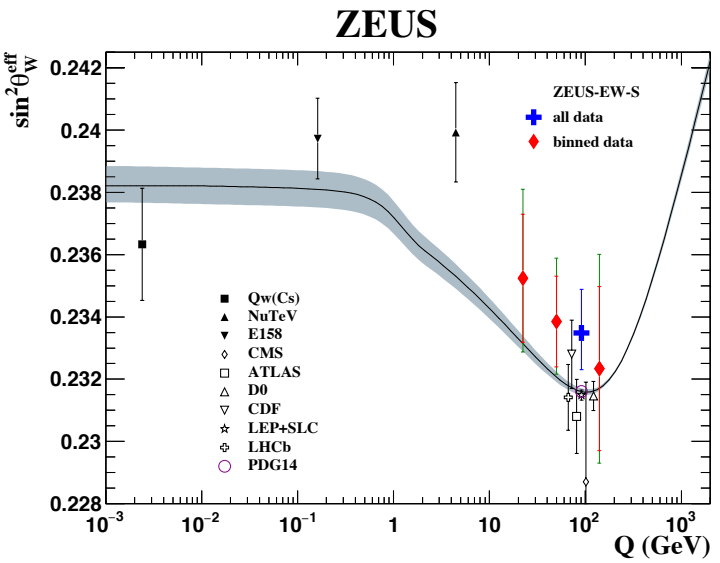
13+4 PDF fit ZEUS-EW-Z to constrain the Z to u,d couplings

Very competitive measurement - at least compared to Tevatron - and can constrain the sign

Combined QCD+EW ZEUS-EW-S

- Dependence on $\sin^2 \theta w$:
  - in the Z propagator
  - In the G_F coupling in CC
  - through the vector coupling of Z to the quarks
  - 13+1 parameter fit

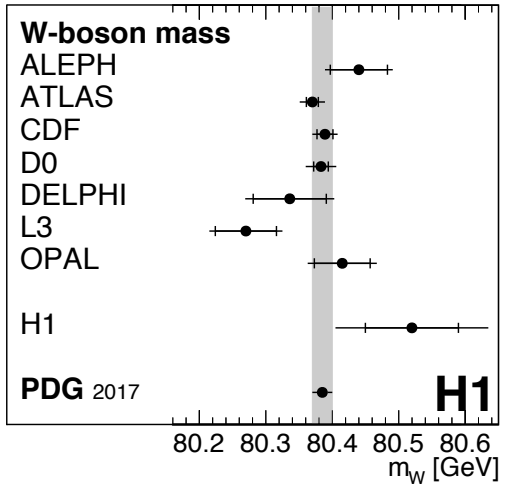
$$\chi_Z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2} \frac{1}{1 - \Delta R} \qquad G_F = \frac{\pi \alpha_0}{\sqrt{2} \sin^2 \theta_W M_W^2} \frac{1}{1 - \Delta R}$$



Phys. Rev. D 93 92016) 092202

- Precision not very high but other text-book plot

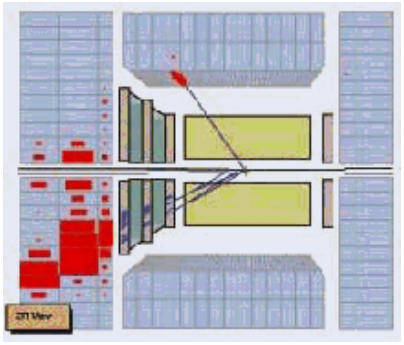
- Similar H1 fit with extraction of W mass in the t-channel (unique measurement)

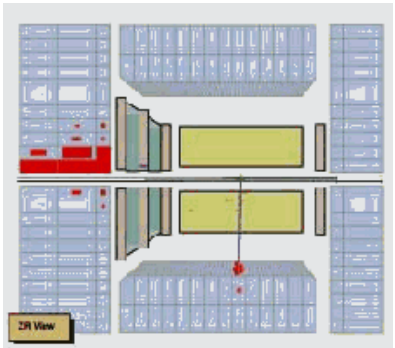


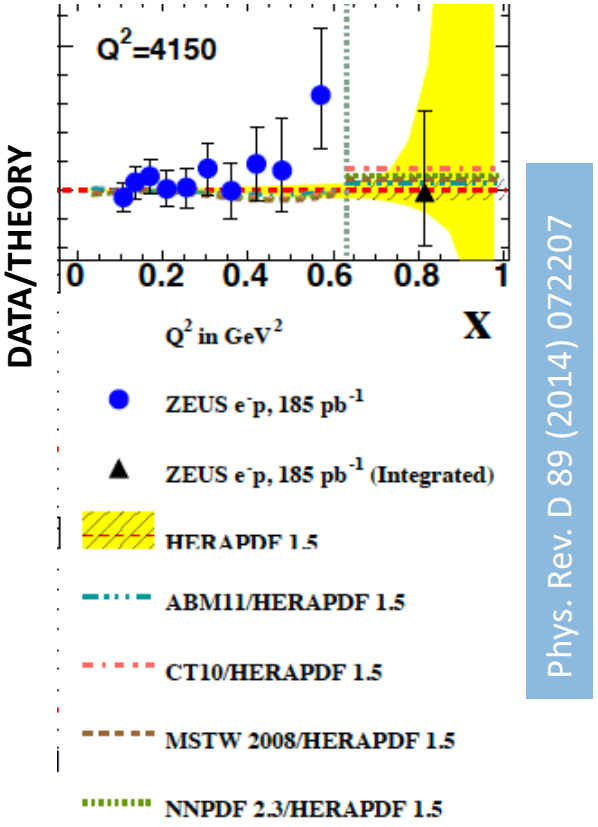
Eur.Phys.J.C78 (2018), 777

Very very high-x

- Let's suppose to have a very high Q^2 electron (reconstructed in the detector) and very high x, so that the jet disappears in the fwd region
- Reconstruct Q^2 from the electron and integrate cross section in x- from edge up to x=1

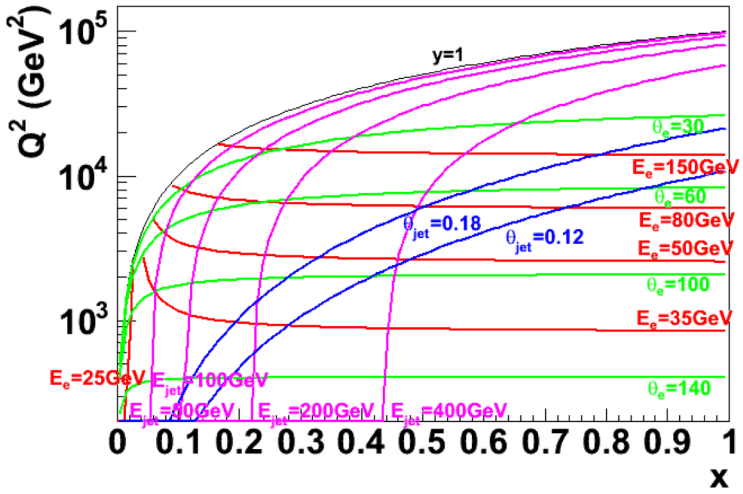






Phys. Rev. D 89 (2014) 072207

A. Caldwell
https://indico.desy.de/indico/event/10523



Uncertainties in PDFs at high-x still very high, these data at x>0.6

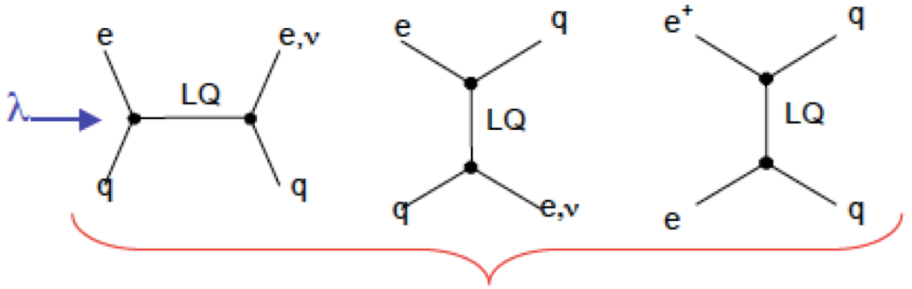
Lessons learned

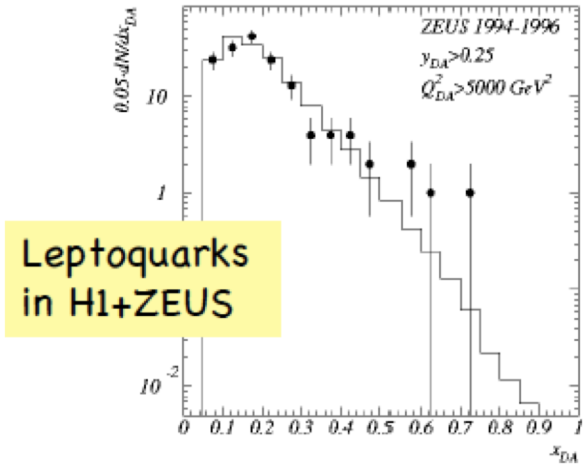
- Precision of scattered electron, hadronic jets is crucial in the whole kinematic range
- Combination H1-ZEUS was fundamental for precision PDFs and electroweak measurements in particular (first one in 2006 for xF_3 !)
- We did not invest enough probably in the polarization measurement – at least at the beginning - its uncertainty as important as the luminosity uncertainty
- Very high x still very unknown region (crucial for searches at the LHC)
- Interaction with theory worked well at HERA, also crucial
- New ideas many years after HERA end (EW fits from 2016)
- Strong attention to PDFs from LHC community

Exotics

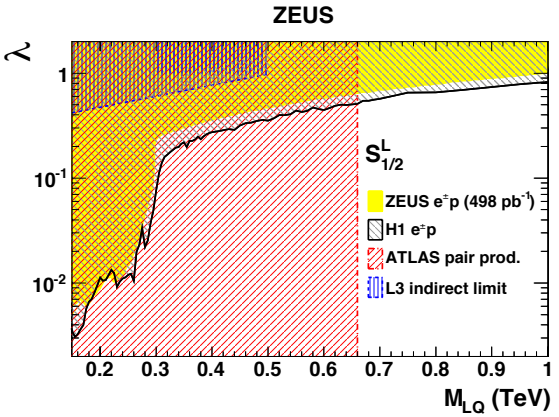
Leptoquarks

- Classical search at HERA, a resonance in x expected
- Early possible signal ~ 200-220 GeV observed with 1996 data by both H1 and ZEUS (at high y), not confirmed later with more statistics
- BRW model used to classify leptoquarks (still used now)
- Competitive limits set at that time, now LHC taking over
- Very modern subject these days for LQs coupling to 3rd generation, due to the B anomalies





Leptoquarks in H1+ZEUS



Phys. Rev. D 86 (2012) 012005

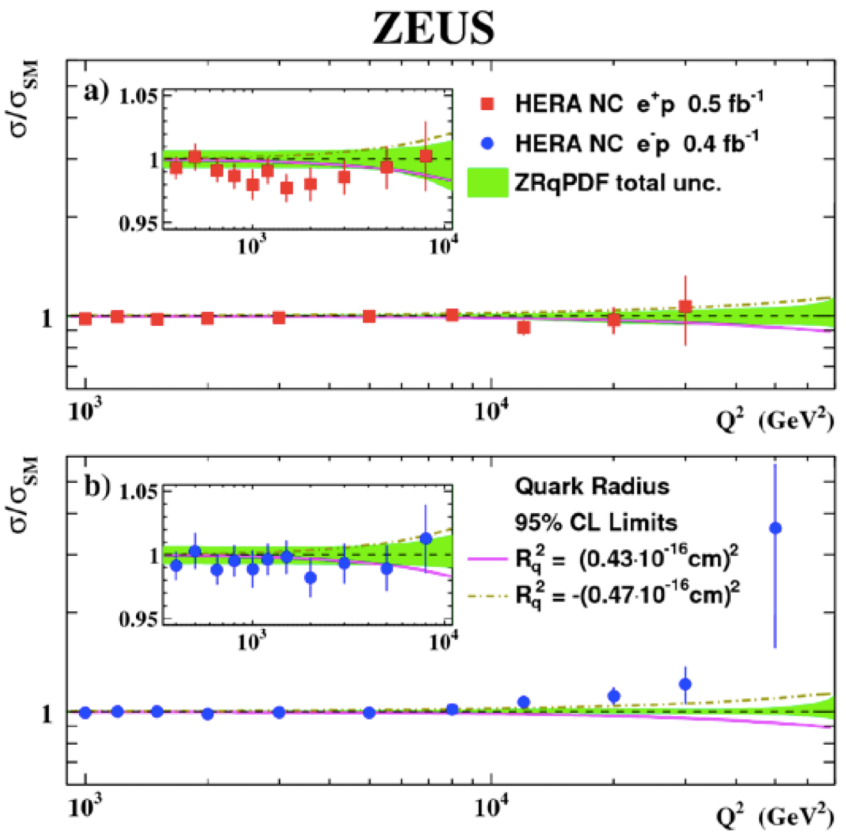
Quark radius and contact interactions

- HERA is the natural place to look for quark substructure.
- It would manifest a deviation from the predicted Q^2 dependence at high Q^2 with an additional quark form factor

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{\mathrm{SM}}}{dQ^2}\left(1-\frac{R_e^2}{6}Q^2\right)^2\left(1-\frac{R_q^2}{6}Q^2\right)^2$$

- QCD fits repeated introducing additional quark radius R_q parameter

$$R_q^2 < (0.43\cdot 10^{-16}\,\mathrm{cm})^2$$

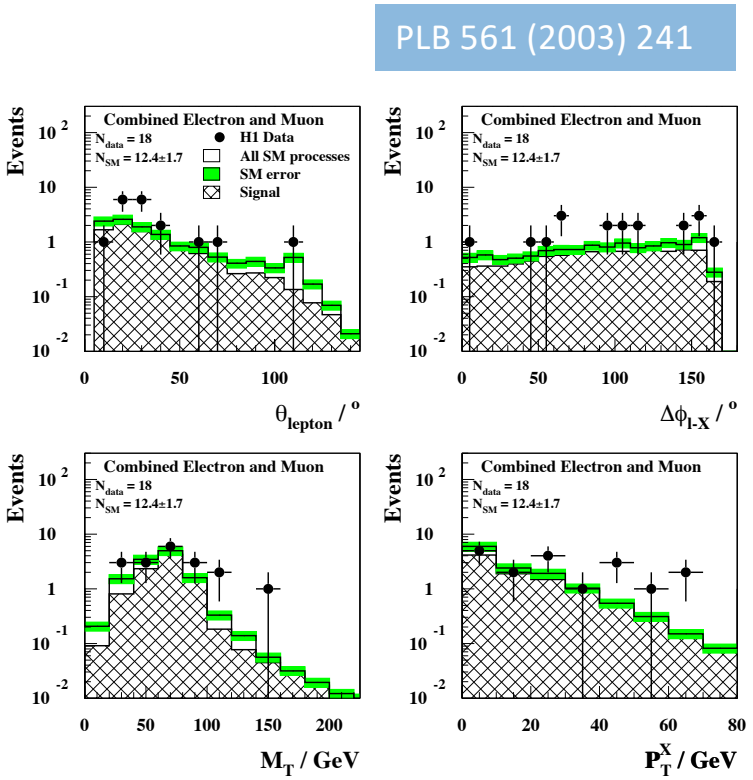


Phys. Lett. B 757 (2016) 468

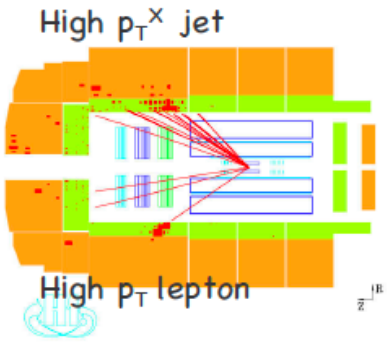
Isolated leptons and p_T^{miss} in H1

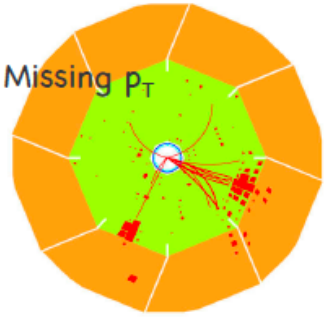
- Events with isolated electrons/muons and large transverse energy
- Main process in W radiation from a quark
- Excess found by H1 at high P_T^X (large p_T of the hadronic system), especially in e^+p collisions
- At $P_T^X > 25$ GeV 10 obs./2.92+/-0.49 exp. with the sample at that time (HERA I)
- Not confirmed by ZEUS, but of course we took it seriously and compared acceptance in a common kinematic range

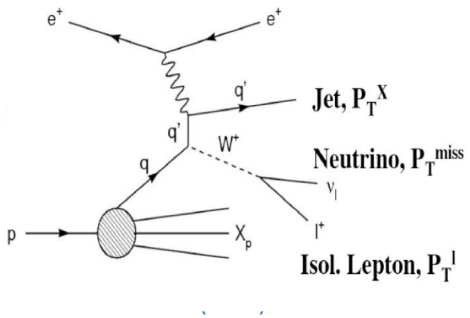
PLB 561 (2003) 241



105 pb^{-1}, e^+p

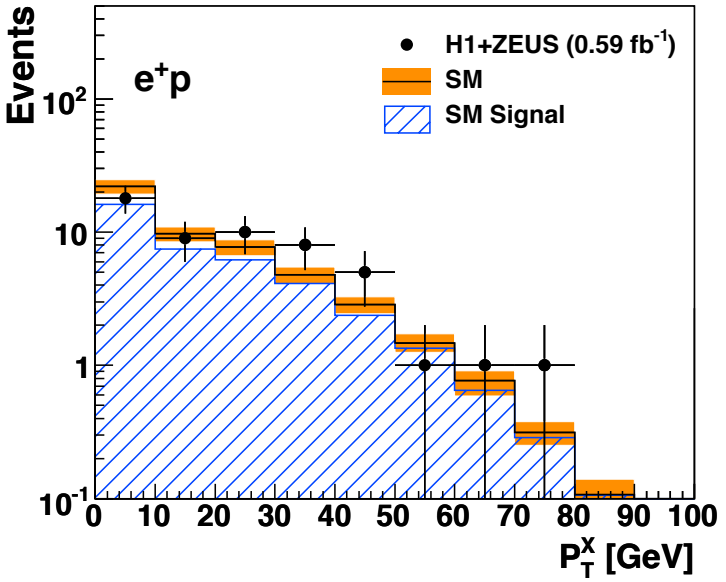




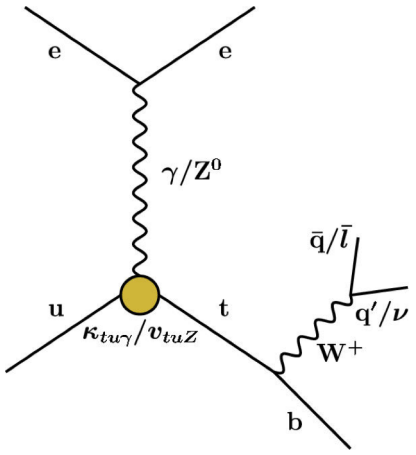


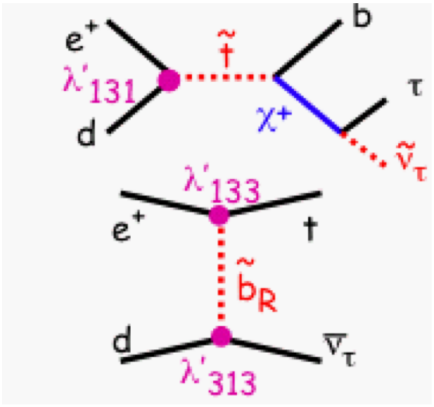
Isolated leptons and p_T^{miss}

- Later combination of all H1+ZEUS at the end of HERA in common phase space
- Possible interpretation: anomalous single-top production with anomalous FCNC u-t coupling or R-parity violation squark production
- Limits set on these couplings



JHEP 03 (2010) 035



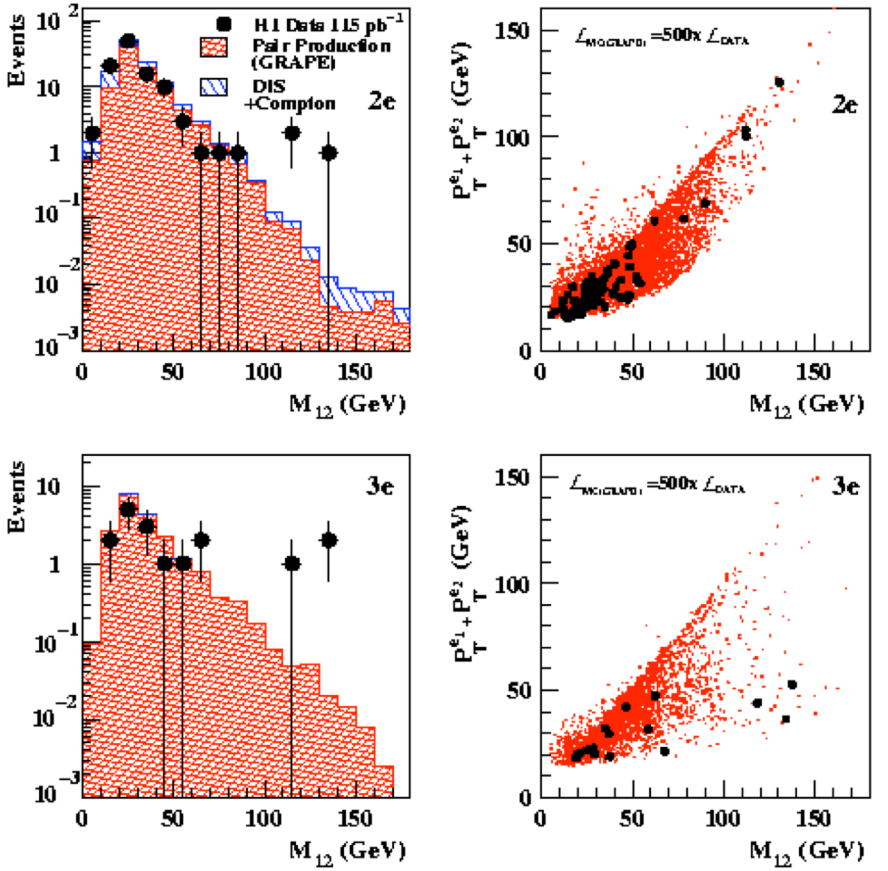


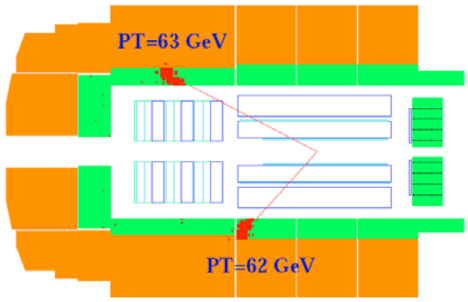
H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Combined	Total	53	49.8 ± 6.2	38.8 ± 5.9	11.1 ± 1.5
	$P_T^X > 25$ GeV	23	14.0 ± 1.9	11.8 ± 1.9	2.2 ± 0.4

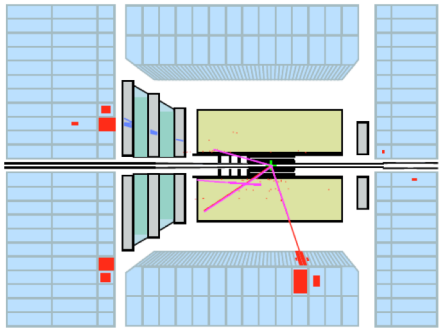
2.9 sigma H1 alone
1.8 sigma combined

Multilepton 2e, 3e events events in H1

- Observation by H1 in events with 2e or 3e events
- A clear excess observed at high invariant mass of the two highest-transverse-energy electrons
- Mostly in positron
- Not confirmed by ZEUS







Possible BSM interpretation: doubly charged Higgs

Multilepton events in H1+ZEUS

- Combination of H1 and ZEUS data with complete dataset

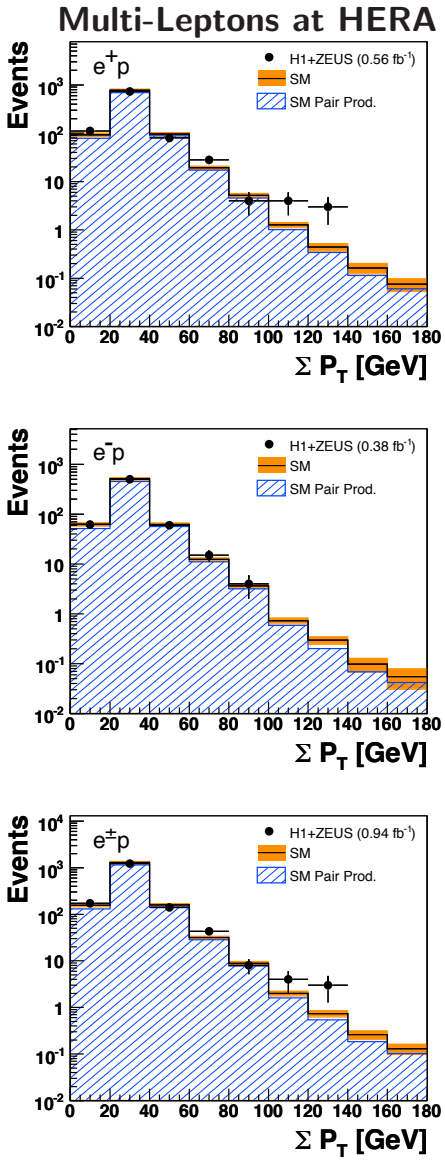
with both electrons and muons in common phase space

- 7 events observed in positron-p collisions at high sum of the p_T , compared to 1.94 expected
- None observed in electron-p collisions
- But in general good agreement
- At least in ZEUS it was crucial to have a precise MC for the background (GRAPE) and an expert on it

Multi-Leptons at HERA ($0.94\ \text{fb}^{-1}$)

$\sum P_T > 100$ GeV

Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e^+p ($0.56\ \text{fb}^{-1}$)	7	1.94 ± 0.17	1.52 ± 0.14	0.42 ± 0.07
e^-p ($0.38\ \text{fb}^{-1}$)	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All ($0.94\ \text{fb}^{-1}$)	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10



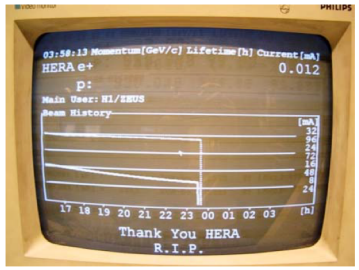
JHEP 10 (2009) 013

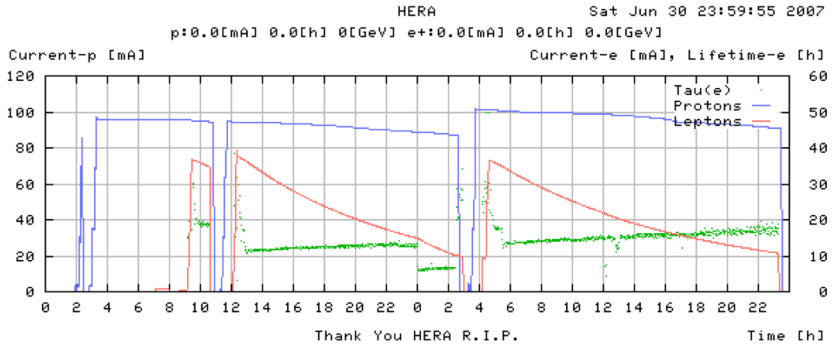
Lessons learned

- Be open to unconventional signatures, not related to a particular BSM model
- Leptons identification crucial (also for tau leptons!)
- MC models for background very important
- Exchange between H1 and ZEUS and combined paper crucial
- Take any deviation seriously, new physics could be hidden in SM precise measurements

Summary

Last fill 30/6/2007 at 23:30





- Picture taken at the party after the last fill
- You have all a new project to start in DIS